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(54) **METHOD AND APPARATUS FOR
MANAGING COMMUNICATION
RESOURCES USING BOOTSTRAP SLOTS**

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(52) U.S. Cl. **370/336; 370/329; 370/347;
370/358**

(58) Field of Search **370/329, 336,
370/337, 345, 347, 348, 349, 460, 443,
459, 458, 468, 436, 342**

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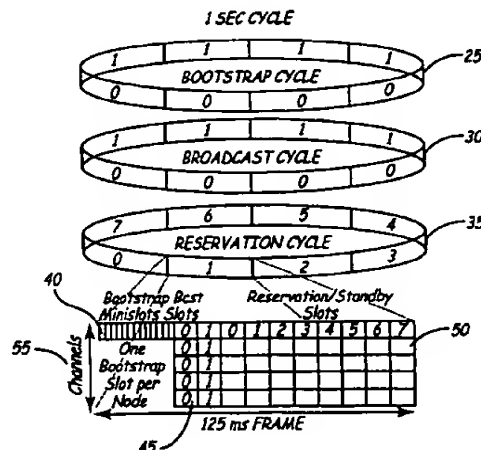
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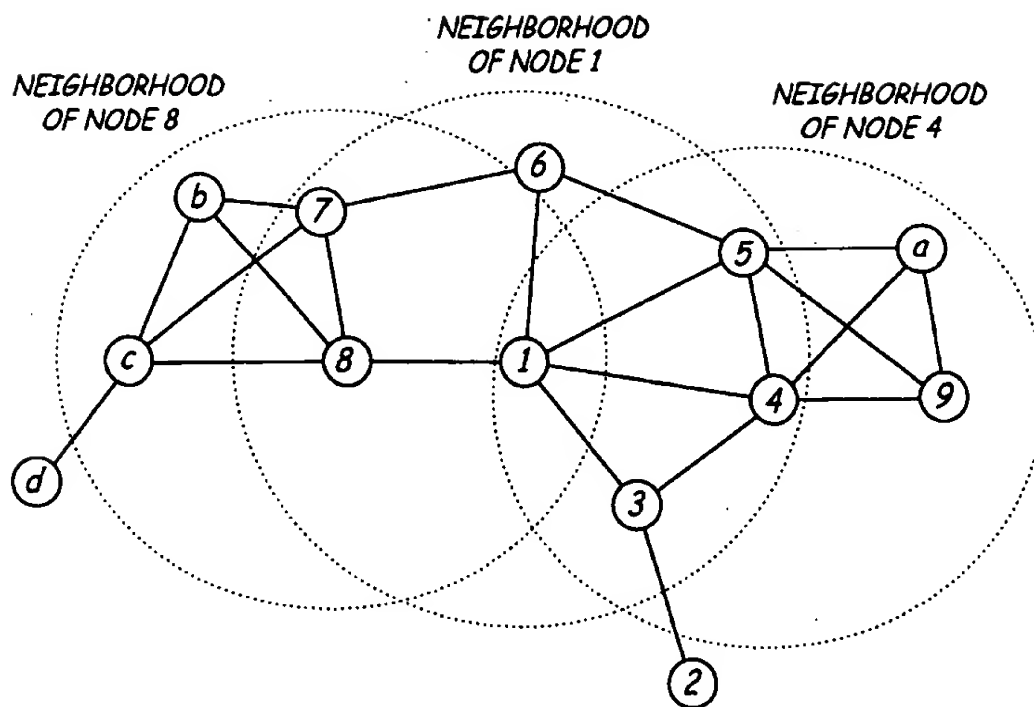
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(57) **ABSTRACT**

A method and system for managing communication
resources between nodes in a network, and more particularly
to a dynamic distributed multi-channel time division mul-
tiple access (TDMA) slot assignment method is presented.
The method and apparatus include a set of higher level
heuristics that enable the wireless channel access scheme to
address predetermined characteristics of the wireless chan-
nel access system. These predetermined heuristics include
using bootstrap slots, adaptive broadcast cycles, channelized
neighborhoods, standby slots, speculation slots, neighbor
segregation, hard circuits, and soft circuits.

14 Claims, 10 Drawing Sheets



**FIG. 1**

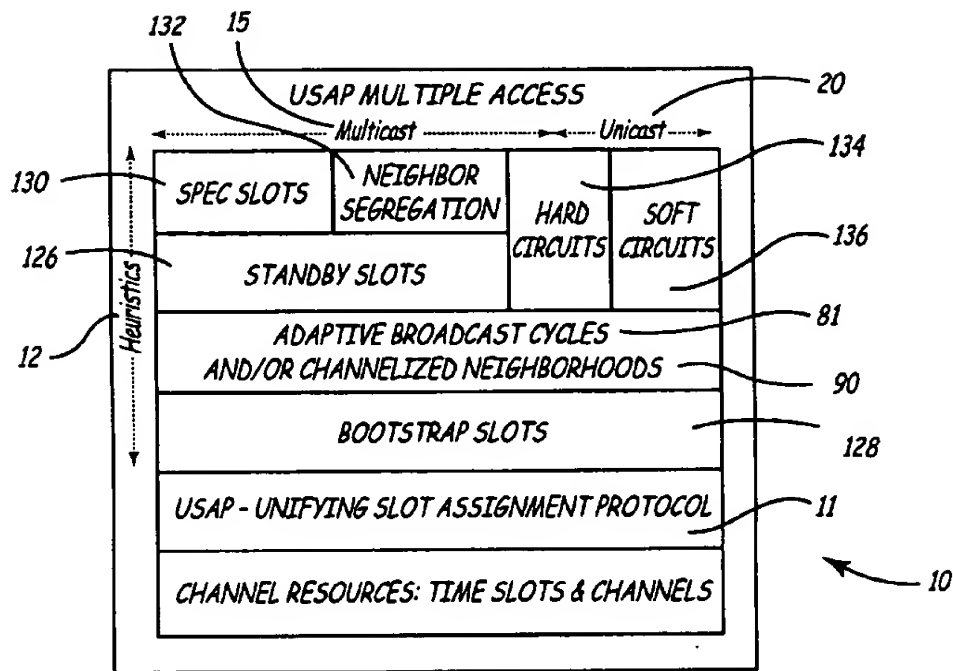
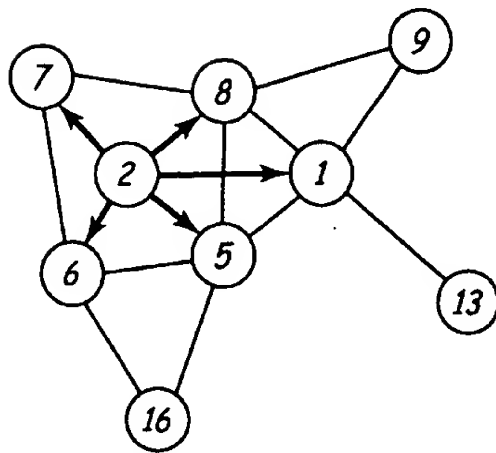
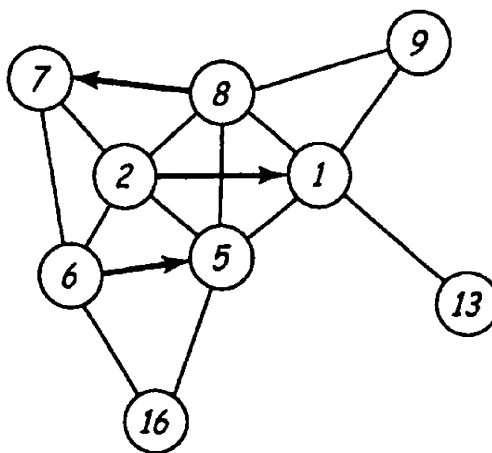


FIG. 2



NODE ACTIVATION

FIG. 3



LINK ACTIVATION

FIG. 4

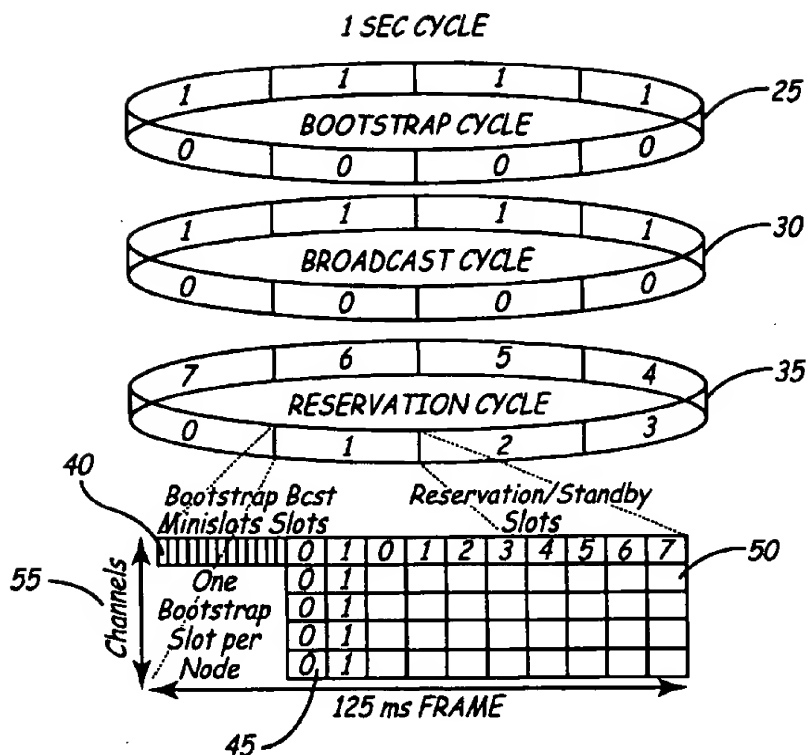


FIG. 5

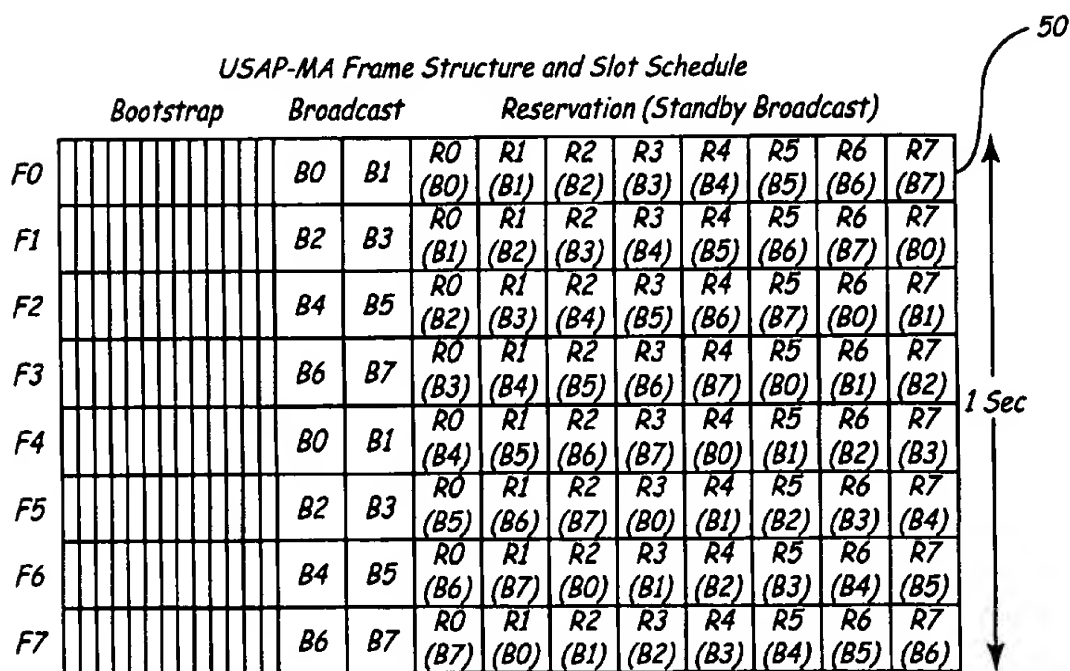
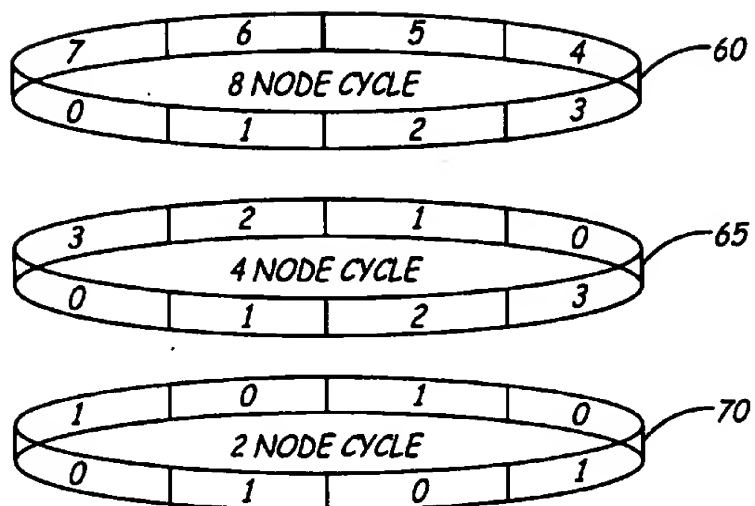
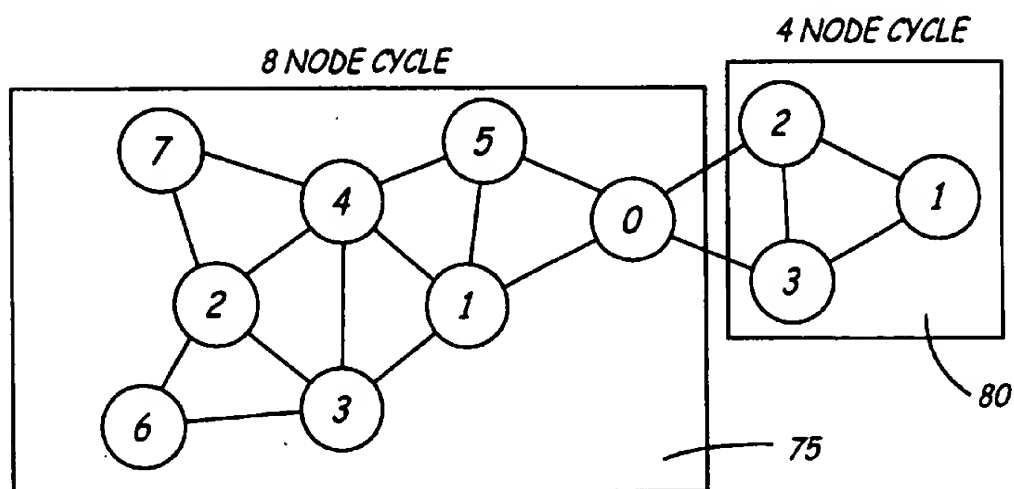
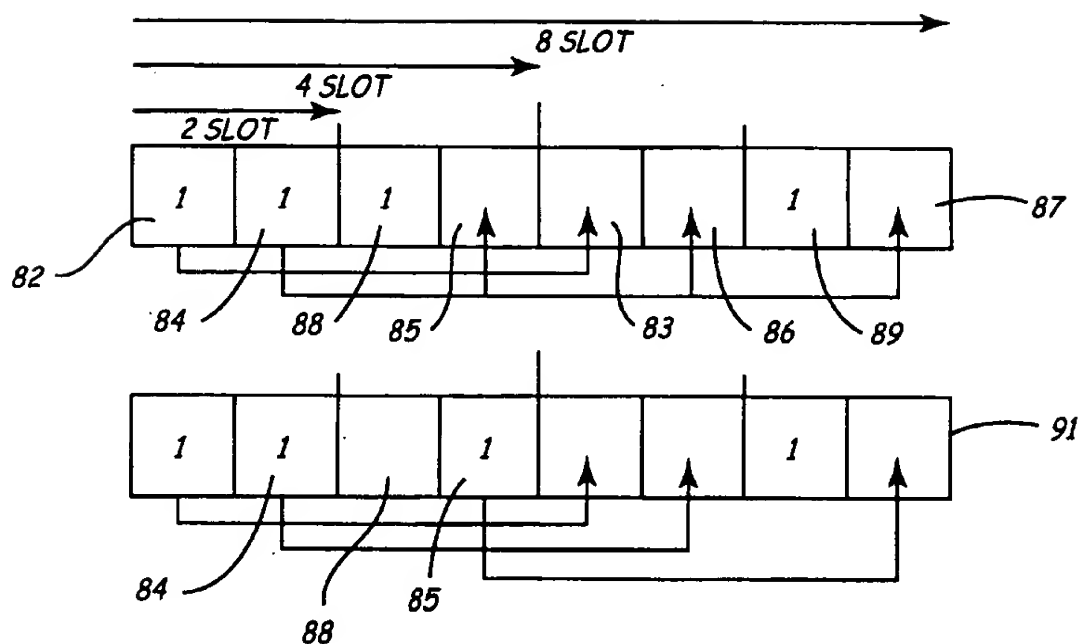


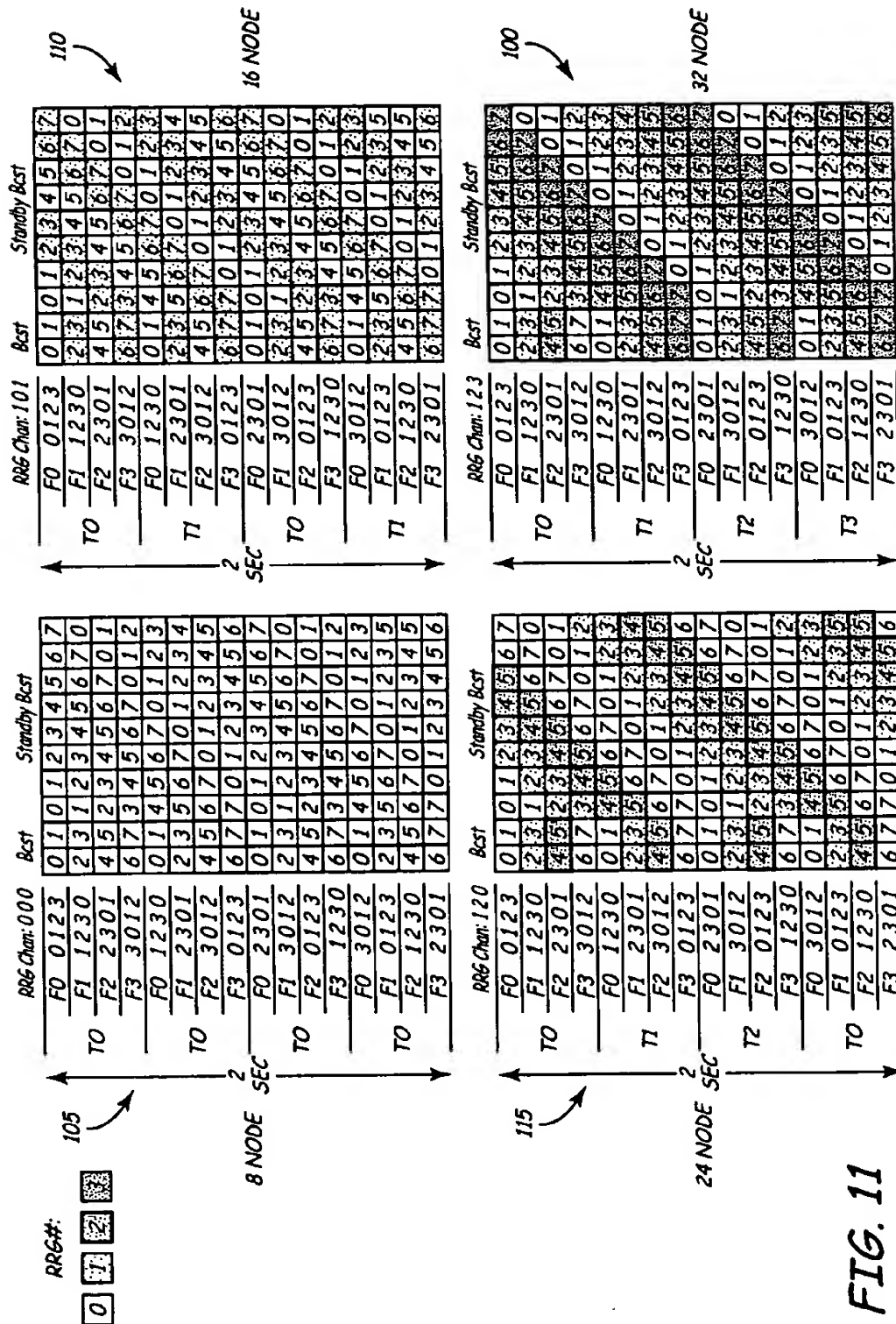
FIG. 6

**FIG. 7****FIG. 8**

Broadcast										Standby Broadcast									
BO	B1	SB0	SB1	SB2	SB3	SB4	SB5	SB6	SB7	BO	B1	SB0	SB1	SB2	SB3	SB4	SB5	SB6	SB7
0	1	0	1	0	1	0	1	0	1	0	1	0	1	2	3	0	1	2	3
0	1	1	0	1	0	1	0	1	0	2	3	1	2	3	0	1	2	3	0
0	1	0	1	0	1	0	1	0	1	0	1	2	3	0	1	2	3	0	1
0	1	1	0	1	0	1	0	1	0	2	3	3	0	1	2	3	0	1	2
0	1	0	1	0	1	0	1	0	1	0	1	0	1	2	3	0	1	2	3
0	1	1	0	1	0	1	0	1	0	2	3	1	2	3	0	1	2	3	0
0	1	0	1	0	1	0	1	0	1	0	1	2	3	0	1	2	3	0	1
0	1	1	0	1	0	1	0	1	0	2	3	3	0	1	2	3	0	1	2
0	1	1	0	1	0	1	0	1	0	2	3	3	0	1	2	3	0	1	2
2 NODE										4 NODE									
0	1	0	1	2	3	4	5	6	7	0	1	0	1	2	3	4	5	6	7
2	3	1	2	3	4	5	6	7	0	2	3	8	9	10	11	12	13	14	15
4	5	2	3	4	5	6	7	0	1	4	5	2	3	4	5	6	7	0	1
6	7	3	4	5	6	7	0	1	2	6	7	10	11	12	13	14	15	8	9
0	1	4	5	6	7	0	1	2	3	8	9	4	5	6	7	8	1	2	3
2	3	5	6	7	0	1	2	3	4	10	11	12	13	14	15	8	9	10	11
4	5	6	7	0	1	2	3	4	5	12	13	6	7	0	1	2	3	4	5
6	7	7	0	1	2	3	4	5	6	14	15	14	15	8	9	10	11	12	13
8 NODE										16 NODE									
0	1	0	1	2	3	4	5	6	7	17	18	0	1	2	3	4	5	6	7
2	3	8	9	10	11	12	13	14	15	19	20	8	9	10	11	12	13	14	15
4	5	16	17	18	19	20	21	22	23	21	22	16	17	18	19	20	21	22	23
6	7	24	25	26	27	28	29	30	31	23	24	24	25	26	27	28	29	30	31
8	9	4	5	6	7	0	1	2	3	25	26	4	5	6	7	0	1	2	3
10	11	12	13	14	15	8	9	10	11	27	28	12	13	14	15	8	9	10	11
12	13	20	21	22	23	16	17	18	19	29	30	20	21	22	23	16	17	18	19
14	15	28	29	30	31	24	25	26	27	31	32	28	29	30	31	24	25	26	27
32 NODE 1st SEC										32 NODE 2nd SEC									

FIG. 9

**FIG. 10**



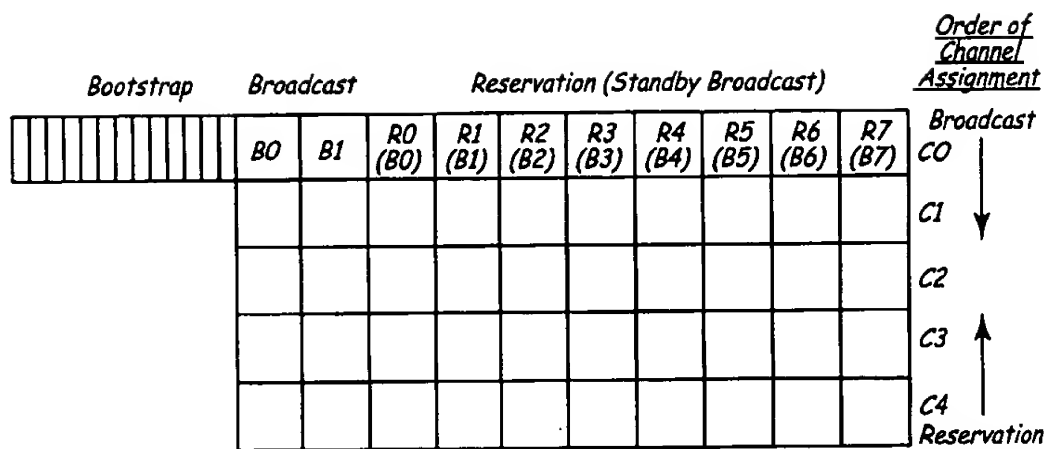
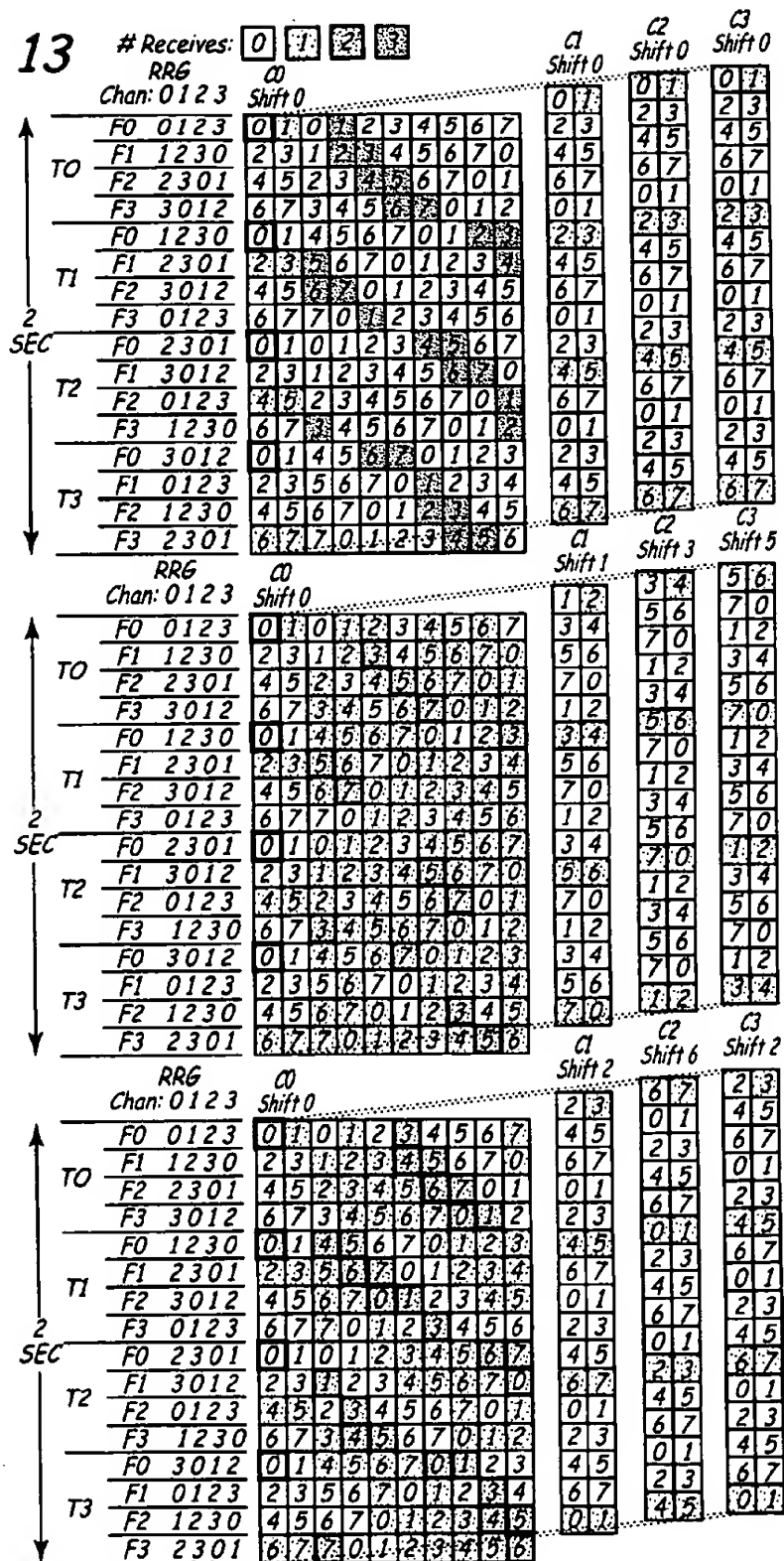
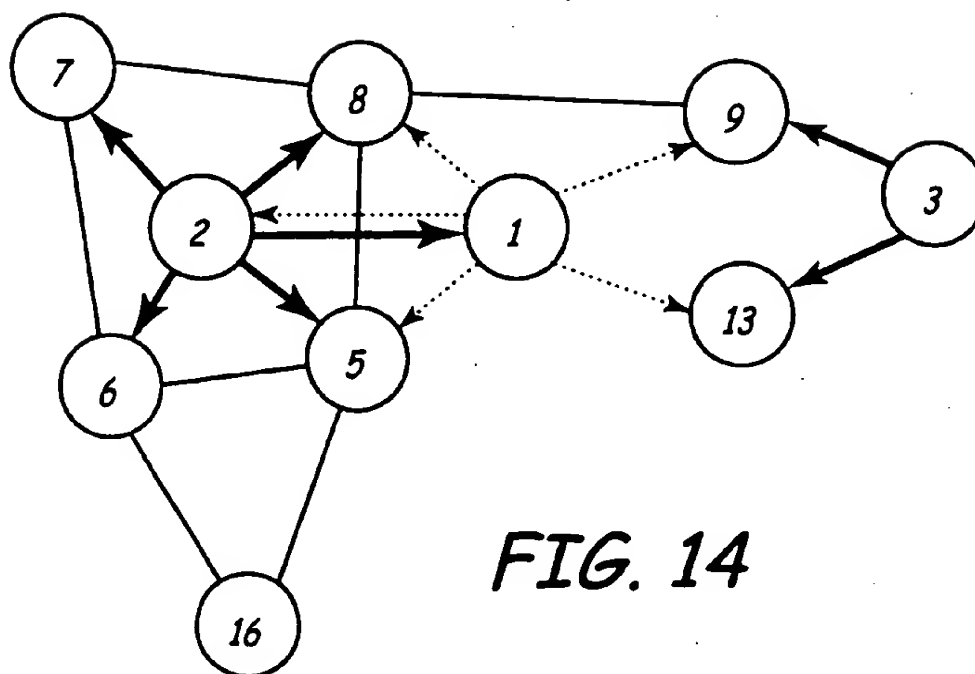


FIG. 12

FIG. 13





1

METHOD AND APPARATUS FOR MANAGING COMMUNICATION RESOURCES USING BOOTSTRAP SLOTS

CROSS REFERENCE TO RELATED APPLICATIONS

Cross-reference is made to related U.S. application Ser. No. 09/303,528, entitled Unifying Slot Assignment Protocol Multiple Access, filed Apr. 30, 1999.

FIELD OF THE INVENTION

The present invention relates to a method for managing communication resources between nodes of a network, and more particularly to a dynamic distributed multi-channel Time Division Multiple Access (TDMA) slot assignment method using bootstrap slots.

BACKGROUND OF THE INVENTION

Mobile multi-hop broadcast packet radio networks are known for their rapid and convenient deployment, self organization, mobility, and survivability. In this type of network as illustrated in FIG. 1, a transmission from one node, for example node 1, is broadcast to all nodes in its "neighborhood". Ultra-high frequency (UHF) systems generally have a neighborhood defined by nodes within line of sight of the transmitting node (these nodes being termed within one "hop" of the transmitting node). For example, in FIG. 1 nodes 1, 3, 4, 5, 6, 7, and 8 make up one neighborhood. For data transmitted from node 1 to propagate multiple hops, the data must be relayed by one or more of node 1's neighbors. For example, node "a" (likewise nodes b, c, and g) is two hops away from the node 1 transmitter. The data will be relayed in this manner until it has arrived at all intended destination nodes.

Since there are generally limitations on the number of simultaneous transmissions that a receiver can successfully process (typically one), collisions can be avoided by the assignment of time slots in which individual nodes can transmit. There are many approaches to deciding which nodes are assigned which slots, and the approach is generally driven by the network applications, such as, broadcast, multicast, unicast, datagrams, virtual circuits, etc. Because the problem of optimally assigning slots in this environment is mathematically intractable, a heuristic approach is taken to design an integrated protocol that both chooses the number of slots to assign to each neighboring node and coordinates their activation in the network.

Tactical military and commercial applications require self-organizing, wireless networks that can operate in dynamic environments and provide peer-to-peer, multi-hop, multi-media communications. Key to this technology is the ability of neighboring nodes to transmit without interference. Neighboring nodes transmit without interference by choosing time slots and channels that do not cause collisions at the intended unicast or multicast receivers. This functionality is provided by the Unifying Slot Assignment Protocol (USAP) which is the subject of U.S. Pat. No. 5,719,868 the disclosure of which is herein incorporated by reference. The function of USAP is to monitor the RF environment and allocate the channel resources on demand and automatically detect and resolve contention resulting from changes in connectivity.

Wireless channel access schemes traditionally come in two flavors: contention and reservation. Contention has been the favorite for ad hoc broadcast networks because its lack

2

of structure lends itself well to the mobile environment. Also, low access delays make it suitable for both tactical voice, where push-to-talk is the norm, and bursty data. However, when the network is heavily loaded contention is inefficient. At that point a structured access like reservation Time Division Multiple Access (TDMA) can achieve much higher efficiencies.

Another division in this field is the difference between broadcast and unicast. Broadcast techniques, in which a node transmits to all of its neighbors, and unicast techniques, in which a node transmits to only one of its neighbors, both have their own unique advantages dependent upon the application. Traditional wireless systems, however, are not capable of utilizing both broadcast and unicast schemes.

Ideally, a wireless channel access system would support both reserved circuits and datagrams in whatever combination is required. Conventional wireless channel access systems however are not capable of supporting both reserved circuits and datagrams.

Conventional wireless communication systems are capable of handling only one or a small number of data types, including low latency voice, delay tolerant data, bursty transactions, high throughput streams, error sensitive data, and error tolerant video. However, conventional systems are not capable of handling the full range of data types.

Conventional wireless communications systems are typically capable of establishing and maintaining only one type of virtual circuit, including either the establishment and maintenance of hard circuits or the establishment and maintenance of permanent datagram service.

Thus, there is a need and desire for a channel access scheme to use TDMA for wireless communication capable of using both broadcast and unicast techniques dependent upon the state of the communication environments. Further still, there is a need and desire for a wireless communication system that is able to handle a full range of data types including low latency voice, delay tolerant data, bursty transactions, high throughput streams, error sensitive data, and error tolerant video. Further still, there is a need and desire for a channel access system that is capable of providing both reserve circuits and datagram service. Further still, there is a need and desire for a wireless communication system that is able to handle the full range of data types while optimizing for densities ranging from fully connected to sparse and, because of its reliance only on local information, scaling to large network sizes.

SUMMARY OF THE INVENTION

The present invention relates to a method for automatically managing communication channel resources between nodes having neighboring nodes in a network of nodes. Each node communicates during specific time slots on a time multiplex basis. The method includes communicating between nodes using a time division multiple access (TDMA) structure, wherein the structure includes time divisions having time frames, the time frames having time slots including bootstrap slots. The method further includes storing, at each node, an assignment of bootstrap slots in a time frame of a time division to nodes in the network, and dynamically adapting the assignment based on density of the network.

The present invention further relates to a communication system having a plurality of transceiver nodes having neighboring nodes in a network and configured to communicate between nodes using a TDMA structure. The TDMA structure includes time divisions having time frames, each time

3

frame having time slots, the time slots including bootstrap slots. The system further includes an assignment table stored at each node which includes assignments of bootstrap slots to transceiver nodes. The system also includes a bootstrap slot assignment protocol to dynamically adapt the assignment table based on density of the network.

The present invention still further relates to a method for automatically managing the communication channel resources between nodes having neighboring nodes in a network of nodes. Each node communicates during specific time slots on a time multiplex basis. The method includes communicating between nodes using a TDMA structure which includes specific time slots during which each node communicates, the specific time slots including bootstrap slots. The method further includes assigning a bootstrap slot to each node, storing a table of assigned bootstrap slots at each node, and adapting the table based on a characteristic of the network.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will become more fully understood from the following detailed description, taken in conjunction with the accompanying drawings, wherein like reference numerals refer to like parts, in which;

FIG. 1 is a general diagram of a network including nodes;

FIG. 2 is a general block diagram of the USAP multiple access system;

FIG. 3 is a diagram illustrating node activation;

FIG. 4 is a diagram illustrating link activation;

FIG. 5 is a diagram illustrating a time division multiple access structure utilized with the present invention;

FIG. 6 is a diagram illustrating the frame structure and slot schedule for the USAP multiple access system;

FIG. 7 is a diagram illustrating exemplary broadcast cycles;

FIG. 8 is a general diagram of a network depicting different broadcast cycles for different nodes;

FIG. 9 is a diagram illustrating different exemplary broadcast schedules;

FIG. 10 is a diagram illustrating an exemplary process of slot poaching;

FIG. 11 is a diagram illustrating a time division multiple access schedule using channelized neighborhoods;

FIG. 12 is a diagram illustrating an exemplary channel assignment order;

FIG. 13 is a diagram illustrating an exemplary shifting transmit schedule for each channel; and

FIG. 14 is a general diagram illustrating a network of nodes showing traffic associated therewith.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

1. USAP Fundamentals

The problem of optimally assigning slots to be practical in a wireless channel access environment is intractable. Prior to USAP, a heuristic approach was typically taken to design an application specific protocol that both chose the number of time slots (hereinafter referred to simply as "slots") to assign to each neighboring node and coordinated their activation. The USAP approach separates the slot assignment mechanism from the heuristic and creates a single generalized protocol for reliably choosing the slots and coordinating their activation. This can then be used to support many

4

different higher layer heuristics for selecting the number of slots to be activated with which neighboring nodes. Because of its inherent ability to tie together diverse higher layer protocols, it is called the "Unifying Slot Assignment Protocol".

Referring now to FIG. 2, a USAP multiple access (USAP-MA) system 10 is depicted. USAP-MA is a channel access system that results from the integration of USAP 11 with a family of heuristics 12 that enable it to satisfy the requirements of mobile multi-hop broadcast packet network and similar self-organizing wireless networks operating in a dynamic environment and providing peer to peer, multi-hop, multi-media communications. USAP-MA supports a collection of requirements in a flexible fashion so that the best instantaneous mix can be achieved to match the applications, the loading, and the topology.

Traditionally, there are two methods in which a node transmits to its neighbors, depicted in FIGS. 3 and 4. As depicted in FIG. 3, node activation describes the technique in which a single transmitting node (here depicted as node #2) broadcasts to all of its neighbors simultaneously rather than on an individual basis. When a transmitter has only one intended receiver (for example transmitter #2 has a single receiver #1 depicted in FIG. 4) it is known as "link activation". The former allows only one active transmitter in a neighborhood while the latter can potentially have several.

Node activation is especially well suited for applications like address resolution and conferencing. Link activation, on the other hand, lends itself better to high volume point-to-point traffic. As depicted in FIG. 2, USAP-MA 10 has heuristics to support both under the more common names of multicast 15 (or broadcast) and unicast 20.

Hereinafter, an ordered pair of RF channel and time slot may be referred to as an "allocation". When a node chooses an allocation, USAP enforces certain constraints to avoid interference within 2 hops of the transmitter. For unicast from node *i* to neighbor *j* it must be an allocation:

that has not already been assigned to either node;

i's neighbors are not receiving in; and

j's neighbors are not transmitting in.

For multicast a node *i* must choose an allocation:

that has not already been assigned to node *i* or any of its neighbors; and

none of *i*'s neighbors' neighbors are transmitting in.

A node insures that its allocations satisfy the above constraints by sharing the following USAP slot sets with its neighbors:

ST_{*i*}—allocations where a node is transmitting;

SR_{*i*}—allocations where a node is receiving; and

NT_{*i*}—allocations where a node's neighbors are transmitting.

To minimize the size of the control packets needed to share this information, it may be more efficient to encode these sets as bit maps or as lists, depending on the number of slots and channels being managed and the density of the network. By exchanging these control packets, USAP has the information it needs to choose non-conflicting transmit allocations consistent with the most recent topology measurements and detect and report conflicts caused by topology changes.

After a transmit allocation is chosen, a node has the option of either using it immediately or waiting until a confirmation is received from each neighbor. The unconfirmed mode is appropriate when it is tolerable to have momentary conflicts due to coincident changes in connectivity or conflicting

5

allocations. The confirmed mode verifies that all neighbors are aware of the allocation and that nothing has happened in the meantime to make it inconsistent with the current topology or other nodes' allocations.

To decide if a slot and a channel are available for either broadcast or unicast transmissions, the USAP methodology may be applied, which is the subject of U.S. Pat. No. 5,719,868 and is described below, however other alternative methodologies exist and could be used in lieu of the USAP methodology.

a. USAP Slot Sets

To choose a slot, a node first generates the set of slots that are not available because they are already in use locally. In the description that follows, the subscript of "i" denotes information about this node and "j" denotes the corresponding information reported by a neighboring node.

Slot Assignments:

S=set of slots

F=set of channels

Self Transmit/Receive Sets:

$STNi(s,f)$ =set of neighbors to which node i transmits on (s,f)

$SRNi(s,f)$ =set of neighbors from which node i receives on (s,f) from which the following sets are derived:

$STi(s,f)=1$ if $STNi(s,f)$ not empty, else 0

$SRI(s,f)=1$ if $SRNi(s,f)$ not empty, else 0

Neighbor Transmit/Receive Sets:

$STj(s,f)$ =the $STi(s,f)$ reported by neighbor j

$SRj(s,f)$ =the $SRI(s,f)$ reported by neighbor j from which the following sets are derived:

$NTi(s,f)=USTj(s,f)$ over all neighbors j of node i

$NRi(s,f)=USRj(s,f)$ over all neighbors j of node i

$NTj(s,f)$ =the $NTi(s,f)$ reported by neighbor j

If node i or its neighbor j is transmitting or receiving (on any channel) in slot s, it is blocked from doing anything else. To this end the following derived sets are useful:

$Bi(s)=STi(s,f) \cup SRI(s,f)$ for any f

$Bj(s)=STj(s,f) \cup SRj(s,f)$ for any f

To decide what slots and channels are available for unicast allocation, a node i constructs the blocked allocations for transmitting to j by excluding allocations

already assigned to either node: $Bi(s) \cup Bj(s)$

i's neighbors are receiving in: $NRi(s,f)$

j's neighbors are transmitting in: $NTj(s,f)$

This information is combined as follows:

$Blocked(i,j,s,f)=Bi(s) \cup Bj(s) \cup NRi(s,f) \cup NTj(s,f)=1$ if i cannot transmit to j in (s,f), else 0

To decide what slots and channels are available for broadcast allocation, a node i constructs the blocked allocations for transmitting to all of its neighbors by excluding allocations

already assigned to i: $Bi(s)$

already assigned to any of its neighbors: $\cup_{j \in \{is_nbrs\}} Bj(s)$

any of i's neighbors' neighbors are transmitting in: $\cup_{j \in \{is_nbrs\}} NTj(s,f)$

This information is combined as follows:

$Blocked(i,s,f)=Bi(s) \cup \cup_{j \in \{is_nbrs\}} Bj(s) \cup \cup_{j \in \{is_nbrs\}} NTj(s,f)=1$ if i cannot transmit to any of its neighbors in (s,f), else 0

b. Reducing Receiver Noise Floor

The data structures of the previous sections are designed to prevent conflicts at a receiver due to multiple transmitters within its neighborhood using the same frequency in the same slot. In some networks it may be desirable to reduce

6

the noise floor at the receivers by adding an additional hop of isolation before an allocation is reassigned. This can be accomplished by defining the set of nodes that are transmitting within 3 hops of node i on an allocation as

$NNTi(s,f)=UNTi(s,f)$ over all neighbors of node i

If this is also included in the control packet and stored at the neighbor of node i as $NNTi(s,f)$ and then the Blocked (i,j,s,f) generated as follows will prevent conflicting transmissions within 3 hops of a transmitter:

$Blocked(i,j,s,f)=Bi(s) \cup Bj(s) \cup NRi(s,f) \cup NTj(s,f) \cup NNTj(s,f)=1$ if i cannot transmit to j in (s,f), else 0

2. TDMA Structure

The objectives of many wireless channel access systems are to support both datagrams and on-demand circuits, low latency voice, and network size, density, and mobility consistent with the tactical battlefield. After considering a number of tradeoffs, USAP-MA may have, in a preferred embodiment, the TDMA structure depicted in FIG. 5, although other structures are possible and, if given other constraints, may be more optimal.

As depicted in FIG. 5, the time division multiple access structure can be viewed as three individual cycles, a bootstrap cycle 25, a broadcast cycle 30, and a reservation cycle 35. Each of the cycles depicted are, in a preferred embodiment, a one second cycle, each of the cycles being divided into eight even frames, each frame being 125 milliseconds in length. (The number of cycles, the length of the cycle, and the length of each frame is a matter of design choice, and should not be viewed as limiting; other numbers of cycles, frame lengths, and cycle lengths may be used without departing from the spirit and scope of the present invention.) Each 125 millisecond frame includes a number of bootstrap minislots 40, broadcast slots 45, and reservation/standby slots 50. Further, each frame includes a plurality of frequencies, shown as channels 55.

The frame length of 125 milliseconds is practical because it is deemed acceptable for voice latency, it divides 1 second evenly, and it allows a manageable number of slots per frame. Bootstrap minislots 40 are used for sharing the critical USAP information necessary to dynamically assign the rest of the slots. With 13 bootstrap slots per frame and a bootstrap cycle of 4 frames, up to 52 nodes can be supported although a technique for managing larger nets may also be incorporated into the system. Broadcast slots 45 are node allocations made to support the datagram service and any other control traffic that nodes need to share. With a broadcast cycle of 4 frames, up to eight (8) nodes can transmit in the 2 broadcast slots or a total of up to 40 nodes on 5 different channels in a neighborhood. Reservation slots 50 repeat every frame so their latency is 125 milliseconds. When a reservation slot has not been allocated it acts as a standby broadcast slot (controlled by standby slot heuristic 126, FIG. 2) assigned to the same transmitter as the corresponding broadcast slot. In addition, the correspondence is shifted by 1 slot every frame as depicted in FIG. 6 (each standby broadcast slot being indicated by the labels (B0) through (B7)), to minimize the impact on the broadcast capacity and latency of any one node when a reservation slot is allocated.

For example, FIG. 6 depicts eight frames representative of a single channel over a one second period. Each frame has eight reservation/standby broadcast slots 50. Each of slots 50 may be either a broadcast slot, represented by (B0) through (B7), or a reservation slot represented by R0 through R7. In the first frame, (B0) is in the first column, in

the second frame (B0) is shifted by one slot to be in the eighth column, in the third frame, F2, (B0) is in the seventh column, and so on until in the eighth frame, F7, B0 is in the second column.

The upshot of the TDMA schedule, depicted in FIG. 6, is that when no reservations are active all slots are fully utilized in support of a broadcast channel that can be used for user datagrams or control traffic. As unicast reservations become active they gradually decrease the capacity of the broadcast channel. Note however that a broadcast reservation actually increases the broadcast capacity of the transmitting node.

3. Bootstrap Slots

For small networks it is most efficient to assign one permanent bootstrap slot per node, but as network size increases this method results in less and less traffic capacity. Thus, it is desirable to have a technique for dynamically assigning these slots (i.e., bootstrap slot heuristic 128, FIG. 2). However, since the bootstrap packets carry the USAP information necessary for contention-free assignment, each node needs initialization information to coordinate itself with its neighbors. Each new or entering node listens for bootstraps from its neighbors before assigning itself a slot and transmitting its own bootstraps. If a conflict occurs, the effected nodes will learn this from their neighboring nodes via the USAP information and choose another slot.

A fixed or dynamic bootstrap assignment system can be used if a dynamic bootstrap assignment method is used, the bootstrap cycle length will depend on the maximum expected neighborhood density. Assuming a network of size N with a maximum degree D (the most neighbors any one node can have), the following formula can be used:

$$L = \min(D^2 + 1, N)$$

The $D^2 + 1$ term is a simple upper bound on the number of colors it takes to do a distance-2 vertex coloring of an undirected graph and this corresponds to the maximum number of bootstrap slots a neighborhood needs for every node to get a slot. (Thus, other formulations for L may be applied without departing from the spirit and scope of the present invention.) One can see that small and/or fully connected networks are best handled by fixed assignments. However, for large networks of reasonable degree the $D^2 + 1$ term yields a smaller cycle. Indeed, this demonstrates that USAP-MA can manage very large networks with a resource management latency that depends only on the maximum neighborhood density. In fact, that latency can be improved significantly for sparser neighborhoods by simply assigning more slots to each node as described below.

An efficient but flexible way to assign more or less slots is to do it in blocks whose size is a power of 2 and whose slots are evenly distributed in the bootstrap cycle. This allows the block to be specified by the first slot index and N where 2^N is the size of the block. In fact, if the first slot indices are chosen to be as small as possible then the size of the blocks can be adjusted up or down with maximum flexibility. This technique is very similar to the Adaptive Broadcast Cycle and Slot Poaching to be described shortly but it deserves its own treatment here. Consider the short broadcast cycle 60 depicted in FIG. 7 that can accommodate up to eight (8) nodes.

Sparser neighborhoods could optimize down to 4 node cycles 65 or 2 node cycles 70 if the nodes continually assign themselves the lowest available slot index, thereby packing themselves into the lower portion of the cycle. Under certain

conditions a node can reuse unassigned slots in the latter part of the cycle if they correspond to its transmit slot on a shorter cycle. A node gleans this knowledge about its neighbors from the USAP information in their bootstraps, as will be described with regards to slot poaching. An exemplary network where this optimization is possible is depicted in FIG. 8.

The nodes in FIG. 8 are numbered by their slot index and the first group 75 has packed themselves into an 8-node cycle. This allows the 3 nodes of second group 50 the right to use a 4-node cycle. It should be noted that the present invention is in no way limited to the configuration or the node cycles depicted in FIG. 8. Any of numerous configurations and node cycles could be used while still achieving a methodology for dynamically assigning bootstrap cycles.

4. Adapting to Network Density

One of the hardest problems to solve in broadcast networks is how to efficiently manage network densities ranging from sparse to fully connected. USAP-MA uses a combination of techniques to solve this problem. To handle sparse neighborhoods the Adaptive Broadcast Cycle 81 (ABC), depicted in FIG. 2, employs nested subdivisions of the fixed length cycle to allow nodes to reuse unused slots. On the other hand, neighborhoods whose density exceeds the capacity of the broadcast cycle utilize Channelized Neighborhoods 90 (CN) to create parallel cycles on other channels so that multiple neighboring transmitters can be active in any given slot. The fusion of these methods results in efficient channel utilization over the entire range of connectivity.

a. Adaptive Broadcast Cycle (ABC)

A number of possible broadcast schedules are depicted in FIG. 9, each for a different neighborhood density, that is, the maximum number of nodes before CN 90 (FIG. 1) takes effect. As depicted in FIG. 9, a number in a slot corresponds to the assigned broadcast slot. In other words, if a node has chosen broadcast slot N , the standby slots with the number N are also its transmit opportunities. They are designed to have the following properties:

They maximize overlap such that a schedule has half of its slots in common with both the previous schedule (shown shaded) and the next schedule. This eases transitions from one schedule to the next as the density changes.

The standby slots are shifted from frame to frame to minimize the impact a reservation slot has on broadcast latency.

A schedule is chosen based on the location of the assigned broadcast slot and any open slots that come after it in the broadcast cycle. If there are open slots corresponding to the assigned slot on a shorter cycle, the node may be able to adopt the shorter cycle as described with regards to slot poaching, described below. To make this work, a node continually looks for empty slots earlier in the cycle and tries to move its broadcast allocation to that slot. This has the effect of packing the allocated slots into the earlier part of the cycle and allowing the cycle to be shortened as density decreases.

b. Slot Poaching

One way to implement ABC 81 (FIG. 1) is to allow a node to transmit in or "poach" unassigned slots according to a shorter cycle if no other transmitter will use them within two hops of this node. This feature exploits the USAP information available at each node, the schedules of nested blocks of 2^k slots, and the fact that a node can be ready to receive in any slot. If the basic broadcast cycle is long enough to

accommodate the maximum network density, poaching will provide shorter cycles for sparser neighborhoods. For instance, poaching would allow an 8-node schedule to achieve the efficiency of a 2 or 4 node schedule whenever possible.

The set of slots P consisting of the original assigned broadcast slot plus the poached slots can be defined as

$$P = \{p | p = i + j2^k\}$$

Where i = index of assigned broadcast slot

$j = 0, 1, \dots, n$ such that $p < \text{basic broadcast cycle}$

k = integer such that 2^k = size of cycle and $i < 2^k$

In order for P to be free of conflicts, the intersection of it with $\text{Blocked}(i, s, f)$ must be empty except for the assigned broadcast slot i . This can be accomplished with the following procedure:

1. Start with the smallest k that satisfies $i < 2^k$.
2. If 2^k is the basic broadcast cycle then no poaching is possible and we are done.
3. If the intersection of P and $\text{Blocked}(i, s, f)$, from USAP, is just i , then P is valid and we are done. Else, increment k and go to 2.

In FIG. 10, an 8 slot basic cycle is represented with the blocked slots marked with a 1. The nodes transmitting in the left half of the cycle try to poach. Slot 82 can poach slot 83 and slot 84 can poach slots 85, 86, and 87. However, slot 88 is blocked by slot 89 and cannot poach. Note however that if slot 88 were to move to slot 85 (depicted in the second cycle 91) then it could poach also, albeit at slot 84's expense. This shows that the packing in the lower part of the cycle can be optimized to maximize the potential for poaching.

A simple proof that this node will not conflict with another node trying to poach the same slot is as follows. Step 1 establishes the smallest poach cycle this node will consider while step 3 increases the size of the cycle if another transmitter is active in P . If there is another active transmitter, it will have an i greater than this node by a factor of 2^k , say $m2^k$, and have a P defined as follows with respect to this node:

$$P = \{p | p = i + m2^k + r2^q\} = \{p | p = i + (m + r2^{q-k})2^k\}$$

Where i = index of assigned broadcast slot of this node

$r = 0, 1, \dots, n$ such that $p < \text{basic broadcast cycle}$

q = integer such that 2^q = size of cycle and $(i + m2^k) < 2^q$

Thus, this node will not consider an unused slot without also considering the slot assigned to the other transmitter ($r=0$) that might also consider that slot, which will disqualify P . Thus, two nodes can not choose the same P .

C. Offline Neighborhoods

Nominally ABC 81 utilizes just one channel. However, if a group of nodes needs to share data at a higher rate than is provided by the datagram service of the broadcast channel, they may utilize one of the other available channels and take advantage of a shorter broadcast cycle to create additional throughput. For instance, a videoconference could be set up that might tax the normal broadcast channel. However, if there were only a few nodes involved and they could afford to temporarily form their own subnet, they could switch to another channel and use a shorter broadcast schedule. Note that they would still maintain contact with the main network via the bootstrap packets in case of an urgent request to return to the main channel. This would not only allow them to greatly increase the throughput among themselves but also, since there are fewer nodes involved, to minimize the control traffic that they must share to maintain the subnet.

5. Channelized Neighborhoods

If the number of broadcast slots is limited to eight (8), communication with more than seven (7) neighbors requires the use of additional broadcast cycles, where cycles can be separated by time or channel that is into channelized neighborhood 90 (FIG. 2). USAP-MA uses the latter approach to maximize channel utilization. For a receiver to hear from each transmitter, it rotates from one channel to another according to the schedule in which a 2-second epoch is broken into four (4) cycles, each of four (4) frames. As depicted in FIG. 11, the schedules for the 8, 16, 24, and 32 node cases are presented. A Rotating Receiving Group (RRG) is made up of the four (4) pairs of nodes that share the same frame on each channel. An RRG will visit a different channel each frame so that at the end of an epoch (in a preferred embodiment an epoch lasts 2 seconds; however, an epoch may be of any defined length) each receiver will get a chance to receive from up to twenty-eight (28) transmitters in a 32-node neighborhood. The reason that not all thirty-one (31) transmitters are heard at every receiver is that the nodes with the same transmit slot will never receive from each other. This has the result that these nodes will not be recognized as logical neighbors even if they are physical neighbors. Communication between them can be achieved over relays or a further optimization can be made to change the RRG memberships each epoch in such a way as to evenly distribute the receive opportunities over time.

The $\{T0, T1, T2, T3\}$ schedule 100 presented for the 32-node neighborhood can be optimized for sparser neighborhoods. In particular, an 8-node neighborhood uses a $\{T0, T0, T0, T0\}$ schedule 105 for single channel operation, a 16-node neighborhood uses a $\{T0, T1, T0, T1\}$ schedule 110 for 2-channel operation, and a 24-node neighborhood uses a $\{T0, T1, T2, T0\}$ schedule 115 for 3-channel operation. Since the perception of neighborhood density can change from one node to the next, the nodes must let each other know each other's schedules. This is done via a couple of bits in the bootstrap. When a node prepares to transmit, it can calculate which of its neighbors will be listening during that time slot according to the schedule in effect at each neighbor. Note that each node always transmits in its allotted time slot and channel. The receivers are the ones that rotate among the transmitters on different schedules depending on the neighborhood density and the RRG they belong to.

a. Channel Assignment Order

USAP-MA uses a further optimization to decrease the impact on the broadcast channel of assigning unicast reservation slots. As depicted in FIG. 12, the USAP-MA has, in a preferred embodiment, five (5) channels available to it numbered 0 to 4 (labeled C0 to C4 in FIG. 12). If the broadcast channels are assigned in the order of 0 to 4 and the reservation slots on channels in the reverse order of 4 to 0, there will be minimal overlap between the broadcast and reservation slots until the network gets heavily loaded. In fact, when a unicast reservation is made on channel 4, it has no impact on the broadcast channel except that the two unicast nodes are unavailable during that slot for broadcast. Furthermore, if reservations were limited to two channels, which still gives much flexibility for unicast assignments, there would be no possibility of reduced broadcast capacity until the neighborhood density reached twenty-four (24) and the broadcast channel spilled onto channel 3. This is yet another example of how USAP-MA maximizes channel utilization while allowing substantially simultaneous contentionless unicast and broadcast transmissions in the same neighborhood.

b. Fair Channelized Schedules

In order to allow all nodes to receive from each transmitter in a fair fashion, it is necessary to periodically change the RRG membership. Recall that the RRG is made up of the four pairs of nodes that share the same frame, where one pair comes from each channel. By shifting the transmit schedule on each channel a different amount each two (2) second epoch a different set of receivers will be active on any particular slot and channel from one epoch to the next. One such shift set {0,1,3,5} results in the following shift schedule for each channel over a 16-second period:

The first three (3) epochs produced by this shift schedule are depicted in FIG. 13, where the active receivers for broadcast slot 0 channel 0 are shown shaded with the degree of shade representing the number of active receivers. Note that in this diagram the times of the receptions are significant only with respect to the frame they occur in. Also, the slot numbers correspond to the assigned broadcast slot. As expected, for the twenty (20) transmissions that each node has per period, there are one hundred forty (140) receptions or seven (7) receivers at a time on each channel. It is plain to see that the distribution of receptions is different for every cycle. What is not so evident is that over the 16-second period each node has an equal number of opportunities to receive each transmitter, but this can be shown with the following analysis:

- (a) In every 4-frame cycle all nodes have an equal opportunity to receive on all channels. This is because during this time each RRG visits each channel once. Thus, during the 16-second period all nodes visit each channel equally.

Since in every 2-second epoch all receivers are active except while transmitting, the transmissions they will miss are the ones either being transmitted on a channel other than the one they are listening to or while they themselves are transmitting. But step (a) shows that they will miss an equal number on all channels, so we must only account for the ones missed while each node is transmitting. In other words, if each transmitter has an equal opportunity of missing transmissions from all other simultaneous transmitters, then the receive opportunities are equal.

Now, in any particular 2-second epoch the simultaneous transmitting nodes on each channel have a relationship specified by the shift schedule of the above table. The table itself corresponds to broadcast slot 0 but there is a similar schedule for the other seven (7) slots. If we can show that each of the simultaneous transmitters for slot 0 misses the same number of transmissions from slot 0 over the 16-second period, then by step 2 the receive opportunities are equal.

It is a simple matter of counting in the table to see that each slot aligns with slot 0 exactly three (3) times per 16-second period so by step (c) the receive opportunities are equal.

One other optimization can be made to minimize the latency that is caused by the clumping of slots each epoch. For example, epoch 0 has 4 receivers in only one or two slots per frame resulting in a latency of a half-second or more between receives opportunities at any particular node. Since other epochs have a more even distribution of receivers per frame worst case latency could be reduced by methodically swapping frames from high latency epochs with corresponding frames in low latency epochs.

6. Error Detection and Retransmission

Some types of traffic benefit from reliable hop-by-hop transmissions. That is, if incorrectly received packets and collisions are detected, the affected packets can be retrans-

mitted. This is achieved in USAP-MA 10 with a bitmap in the bootstrap packet representing each slot in the frame where each bit means that a packet was correctly received in the corresponding slot. If a node had previously transmitted in a slot then it can tell if its intended receiver(s) correctly received the packet and if not then retransmit it. This technique applies equally well to transmissions in the broadcast, standby, and reservation slots. Of course, some types of traffic, such as voice traffic, do not benefit from retransmissions. Thus, the retransmission facility can be applied selectively.

7. Contention Access or Spec Slots

There are circumstances when traffic is sporadic and bursty. Traditionally this is most efficiently handled by contention access while reservation access is most efficient under heavy loads. Now, in the absence of allocations USAP-MA 10 effectively reserves all slots, either permanently or temporarily, for neighbors to broadcast in. However, under conditions where contention access is desirable, it would be more efficient to allow nodes to transmit in standby slots that do not belong to them but that are going to be idle for lack of traffic. In other words, if a node knows that in the upcoming frame it is not going to need its standby slot, it could announce this fact in the bootstrap packet (StandbyFree) at the beginning of the frame so that another node could transmit in that slot if needed. The other node can then determine (1) if it can effectively use the slot and (2) if there is a good chance that the intended receiver(s) will hear its transmission, hence the term "Spec (ulation) Slot" 130 (FIG. 2). Since there is contention for the slot, there may be collisions but these can be compensated for using the error detection already described.

A node receiving a bootstrap with StandbyFree set would consider using this neighbor's standby slot if it currently had more traffic than it could send in its reserved slots in this frame. If so, it would determine if any of its queued traffic were addressed to neighbors who would normally be listening on the right channel. This would include the original neighbor and any other neighbor that it and this node have in common. Now, if any of these common neighbors happen to also use the slot speculatively then there may be a collision, depending on the location of the intended receivers with respect to the transmitters. To determine if any of its neighbors are listening on the right channel a node consults the USAP self-receive tables (SRi) for each neighbor. Alternatively, a node could more accurately calculate the chances of collision if the bootstrap Assigned Slot Record (ASR) also contained NRi, which would yield whether a neighbor is allowed to transmit. Furthermore, to determine if these neighbors are in common with the original transmitting node, a node will need to consult its routing information. Once qualified neighbors are identified, traffic for them can be queued up to go out in the slot.

As an example, consider that node 2 in FIG. 14 might announce StandbyFree as set. If node 1 had excess traffic that it wished to send to nodes 2, 5, and/or 8 it could use node 2's standby slot as a spec slot, assuming that node 3 was not transmitting at the same time on the same channel. Otherwise there would be a collision at nodes 9 and 13. This is the reason for checking that all of the potential receivers of 1's speculative transmission are neighbors of node 2. Since this information is normally not stored by USAP it must be obtained elsewhere, possibly from the routing protocol.

8. Bootstrap Packet Format

The bootstrap packet consists almost entirely of the USAP assigned slot sets STi, SRi, and NTi. The broadcast and

reservation slots are managed separately and encoded slightly differently. There is a map of two (2) bit fields that correspond to every slot, yielding two (2) bits * 8 slots * 5 channels=80 bits for the reservation slots and 2 bits * 8 slots=16 bits for the broadcast slots. The two (2) bit fields are combined into what is called the Assigned Slots Record (ASR) and are interpreted as follows:

USAP regenerates the STi, SRi, and NTi sets from the ASR when it receives a bootstrap packet from a neighbor. In addition, there is

- 1 bit for StandbyFree;
- 1 bit for USAP confirmation;
- 2 bits to indicate which of 4 channels the broadcast slots are used on;
- 2 bits for channelized neighborhood cycle (8, 16, 24, or 32-node);
- 4 bits for 16 second synchronization;
- 24 bits to identify up to 4 6 bit receiver Ids for unicast reservations; and
- 10 bits for error detection.

In this way the entire functionality of USAP-MA 10 described up to this point is packed in about eighteen (18) bytes. Alternatively, this eighteen (18) byte packet may be of any size that is suitable for the given resources and should not be considered limiting.

9. Neighbor Segregation

A problem with adapting transmission parameters on a broadcast channel is that a node may have to use parameters that work with the worst neighbor to insure that all nodes receive the broadcast. A worst case scenario is when a node has a set of good quality neighbors that it would normally be able to transmit to at a high rate but it is stuck using a low rate to achieve reliable transmissions to a single poor neighbor.

The USAP-MA 10 solution is to segregate neighbors (controlled by neighbor segregation heuristic 132, FIG. 2) into 2 (or more) groups and adjust the transmission parameters to each of them independently. In this way a node could transmit to its good neighbors at an efficient high rate and its poor neighbors at a robust lower rate.

Of course, in order to use two different rates, a node either needs to have different transmission opportunities or be able to change rates in the middle of a packet. Between the broadcast and standby slots a node nominally has two broadcast opportunities. Since the standby slot has lower latency and the potential for higher throughput it makes sense to use it for the high quality neighbors and use the broadcast slot for the poorer neighbors. Of course, if all neighbors are equally good then both slots can be used interchangeably.

Packets that must go to all neighbors (like routing updates) or to one or more of the poor neighbors would thus use the broadcast slot. Packets destined for the good neighbors would use the standby slot unless there was room in the broadcast slot left over. Note that the routing should tend to favor the good neighbors, thereby directing most of the packets into the higher rate standby slot.

Besides the increased efficiency of transmitting at higher rates, neighbor segregation also allows the receivers to sample a greater number of data rates, enabling them to better choose the proper transmission parameters for their neighbors.

10. Soft Circuits

One of USAP's strong points is its ability to make allocations on the fly. Since it constantly maintains up-to-date knowledge via the bootstrap packets of the active allocations in its neighborhood, it is always ready to allocate a new transmit slot. Nominally the new allocation must be announced in only one bootstrap before it can be used. Certain types of applications can take advantage of this to eliminate the setup delays and inflexibility of hard circuits 134 (FIG. 2), that is, reserving slots all along a path from source to destination before turning on the traffic. In particular consider voice and video. Once started they continuously supply data that loses its value if it is not delivered very quickly. They are also both tolerant of small amounts of dropped data and data arriving out of order, resulting in small glitches of little consequence to the users.

Now consider a heuristic that simply assigns enough slots on its outgoing links to satisfy the requirements of the traffic entering it. This would allow traffic to push its way through the network reserving the channel resources along the way. When the traffic stops the allocations are automatically released. Called a "soft circuit" 136 (FIG. 2), this heuristic has essentially the same effect as a dedicated circuit setup: if enough slots are available, they are allocated to support the traffic stream. The difference is that it is executed locally at each node rather than coordinated at the end points. Also, the soft circuit heuristic will attempt to fix a broken link locally by routing around it if possible instead of reporting the failure all the way back to the source. Thus, by taking advantage of certain characteristics of the data streams and effectively utilizing the capabilities of USAP 11, soft circuits provide fast, robust support for certain applications.

USAP 11 can manage the resource allocations for many types of TDMA architectures that operate in a distributed dynamic environment. The user needs and application requirements drive the design of heuristics to cause USAP to assign the right mix of permanent or on-demand allocations. USAP-MA is an example of such an integrated family of heuristics that supports the requirements of the tactical military and commercial environment. It does this by providing broadcast and unicast transmissions, datagrams for bursty data and hard and soft circuits for high capacity or low latency streams, selective hop-by-hop reliability to minimize end-to-end retransmissions, sparse and dense neighborhood optimizations, and the ability to scale to large networks.

It is understood that while the detailed drawings and examples given describe preferred exemplary embodiments of the present invention, they are for the purposes of illustration only. The method and apparatus of the invention is not limited to the precise details and conditions disclosed. For example, it is not limited to the specific time frame and time slot lengths, or to the number of cycles, or to the inclusion of all of the heuristics discussed. Further, the protocols discussed herein, such as the standby heuristic, the adaptive broadcast cycle heuristic, the bootstrap slot heuristic, the speculation slot heuristic, the channelized neighborhood heuristic, and the neighbor segregation heuristic, may be developed using approaches other than a heuristic approach, such as a deterministic or probabilistic

15

approach, or any combination thereof. Various changes may be made to the details disclosed without departing from the spirit of the invention, which is defined by the following claims.

What is claimed is:

1. A method for automatically managing communication channel resources between nodes having neighboring nodes in a network of nodes, wherein each node communicates during specific time slots on a time multiplex basis, the method comprising:

communicating between nodes in the network using a time division multiple access structure, the time division multiple access structure including time divisions having time frames, each time frame having a plurality of time slots, the plurality of time slots including bootstrap slots;

storing, at each node, an assignment of bootstrap slots in a time frame of a time division to nodes in the network; dynamically adapting the assignment of bootstrap slots based on density of the network;

wherein dynamically adapting the assignment of bootstrap slots includes:

determining, at a node, which bootstrap slots are assigned to the neighboring nodes of that node;

self-assigning, at that node, a first assignment of a bootstrap slot that is not assigned to its neighboring nodes; and

transmitting, from that node to its neighboring nodes, a communication during that node's self-assigned bootstrap slot, the communication notifying its neighboring nodes of the first assignment of the bootstrap slot.

2. The method as recited in claim 1, further comprising: self-assigning an alternative bootstrap slot if the first assignment creates a conflict.

3. The method as recited in claim 1, wherein dynamically adapting the assignment of bootstrap slots includes:

assigning bootstrap slots to a particular node in the network in a block of bootstrap slots, the number of bootstrap slots in the block being equal to 2^N (two raised to the power of N), wherein N is the number of nodes in the network.

4. The method as recited in claim 1, wherein dynamically adapting the assignment includes:

defining a first bootstrap cycle having a first half cycle and a second half cycle;

identifying when a particular node and its neighboring nodes each have an assigned bootstrap slot in the first half cycle and no assigned bootstrap slots in the second half cycle; and, if so, then

establishing a second bootstrap cycle in which the particular node and its neighboring nodes each have an assigned bootstrap slot, the second bootstrap cycle being shorter than the first bootstrap cycle.

5. The method as recited in claim 1, further comprising: maintaining substantially contention free access to the communication channel resources by implementing a unifying slot assignment protocol.

6. A communication system, comprising:

a plurality of transceiver nodes arranged in a network and configured to communicate between transceiver nodes using a time division multiple access structure, each transceiver node having neighboring nodes,

the time division multiple access structure including time divisions having time frames, each time frame having time slots, the time slots including bootstrap slots;

16

an assignment table stored at each transceiver node, the assignment table including assignments of bootstrap slots to transceiver nodes; and

a bootstrap slot assignment protocol to dynamically adapt the assignment table based on density of the network, wherein the bootstrap slot assignment protocol dynamically adapts the assignment table stored at a transceiver node by determining which bootstrap slots are assigned to that transceiver node's neighboring nodes, newly assigning to that transceiver node one of the bootstrap slots that are not assigned to the neighboring nodes, and transmitting a communication to the neighboring nodes in the newly assigned bootstrap slot, the communication representing a notification of the new assignment.

7. The communication system as recited in claim 6, wherein the bootstrap slot assignment protocol assigns a different bootstrap slot to transceiver node in the event the new assignment creates a conflict with other assignments of bootstrap slots.

8. The communication system as recited in claim 6, wherein the bootstrap slot assignment protocol assigns bootstrap slots in blocks to transceiver nodes in the network, the number of bootstrap slots in each block being equal to 2^N (two raised to the power of N), wherein N is the number of transceiver nodes in the network.

9. The communication system as recited in claim 6, wherein the bootstrap slot assignment protocol defines a first bootstrap cycle having a first half cycle and a second half cycle, determines whether a particular transceiver node and its neighboring nodes each have an assigned bootstrap slot in the first half cycle and no assigned bootstrap slots in the second half cycle, and, if so, then establishes a second bootstrap cycle for the particular transceiver node and its neighboring nodes to transmit communications, the second bootstrap cycle being shorter than the first bootstrap cycle.

10. The communication system as recited in claim 6, further comprising a unifying slot assignment protocol to maintain substantially contention-free access to communication resources of the network.

11. A method for automatically managing communication channel resources between nodes having neighboring nodes in a network of nodes, wherein each node communicates during specific time slots on a time multiplex basis, the method comprising:

communicating between nodes using a time division multiple access structure, the time division multiple access structure including specific time slots during which each node communicates, the specific time slots including bootstrap slots;

assigning a bootstrap slot to each node;

storing a table of assigned bootstrap slots at each node; and

adapting the table based on a characteristic of the network;

wherein adapting the table includes:

determining which of the bootstrap slots are assigned to a node's neighboring nodes;

newly assigning to that node a bootstrap slot that is not assigned to that node's neighboring nodes; and transmitting, from that node, a communication during the newly assigned bootstrap slot.

12. The method as recited in claim 11, wherein adapting the table includes assigning a block of bootstrap slots to a

17

node, the number of bootstrap slots in the block being equal to 2^N (two raised to the power of N), wherein N is the number of nodes in the network.

13. The method as recited in claim 11, further comprising:
defining a first bootstrap cycle having a first half cycle and
a second half cycle;
determining whether a node and its neighboring nodes
each have an assigned bootstrap slot in the first half
cycle and do not have an assigned bootstrap slot in the
second half cycle; and, if so, then

18

establishing a second bootstrap cycle in which the node
and its neighboring nodes each have an assigned boot-
strap slot, the second bootstrap cycle being shorter than
the first bootstrap cycle.

14. The method as recited in claim 11, further comprising:
maintaining substantially contention-free access to the
communication channel resources by using a unifying
slot assignment protocol.

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